US008065785B2

(12) **United States Patent**
Brown et al.

(10) **Patent No.: US 8,065,785 B2**
(45) **Date of Patent: Nov. 29, 2011**

(54) **METHOD FOR PRODUCING A TURBULENCE CONDITIONER FOR USE WITH AN ULTRASONIC FLOW METER IN A PIPE**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **12/807,193**

(22) Filed: **Aug. 31, 2010**

(65) **Prior Publication Data**

US 2011/0005335 A1 Jan. 13, 2011

Related U.S. Application Data

(62) Division of application No. 12/002,270, filed on Dec. 14, 2007, now Pat. No. 7,823,462.

(51) **Int. Cl.**
B23P 17/04 (2006.01)

(52) **U.S. Cl.** **29/592**

(58) **Field of Classification Search** .. 73/861.26–861.28; 29/592
See application file for complete search history.

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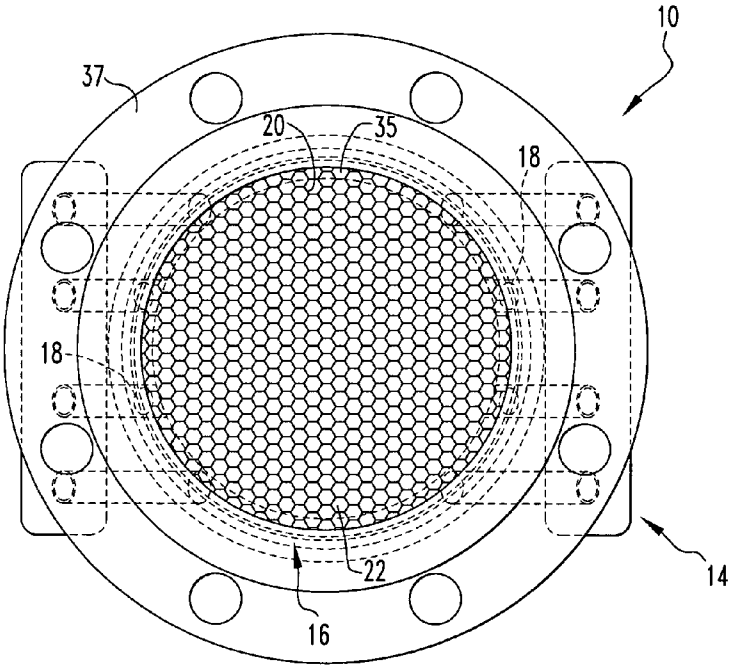
(74) *Attorney, Agent, or Firm* — Ansel M. Schwartz

(57) **ABSTRACT**

A method for producing a turbulence conditioner for use with an ultrasonic flow meter in a pipe having the steps of identifying an effective diameter of an aperture of the flow meter to be disposed in an opening in the pipe through which the flow meter communicates pulses of ultrasonic energy with the interior of the pipe. There is the step of building a conditioner with a pitch between openings in the conditioner which is less than the effective diameter.

8 Claims, 13 Drawing Sheets



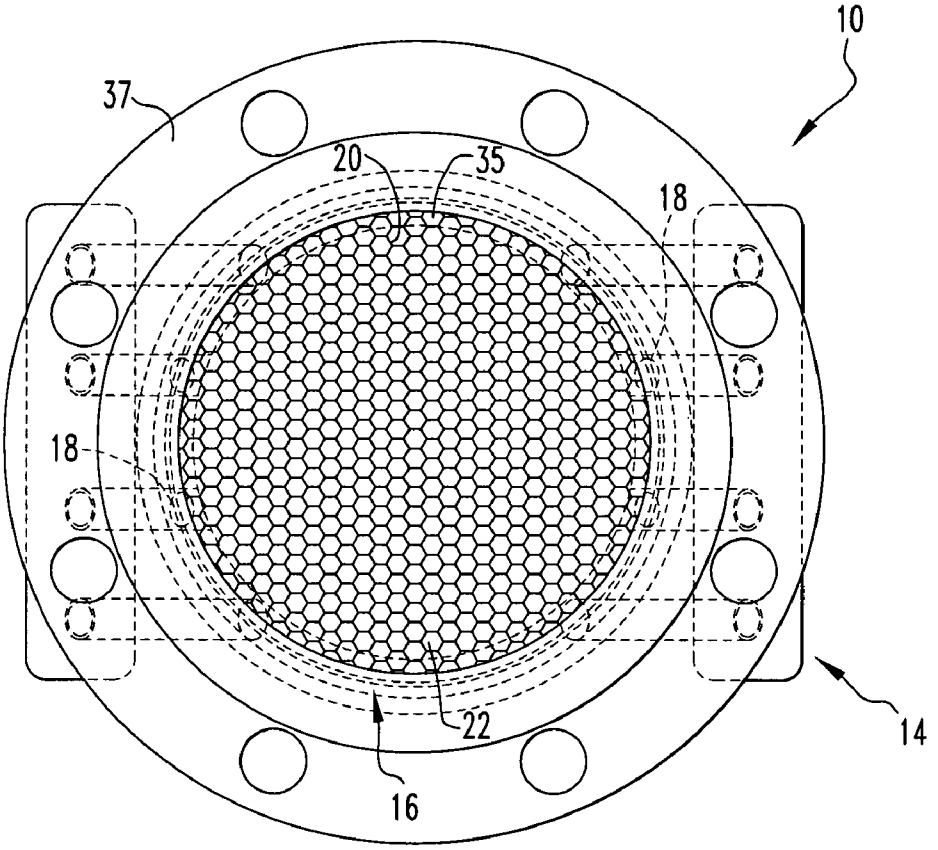


FIG.1A

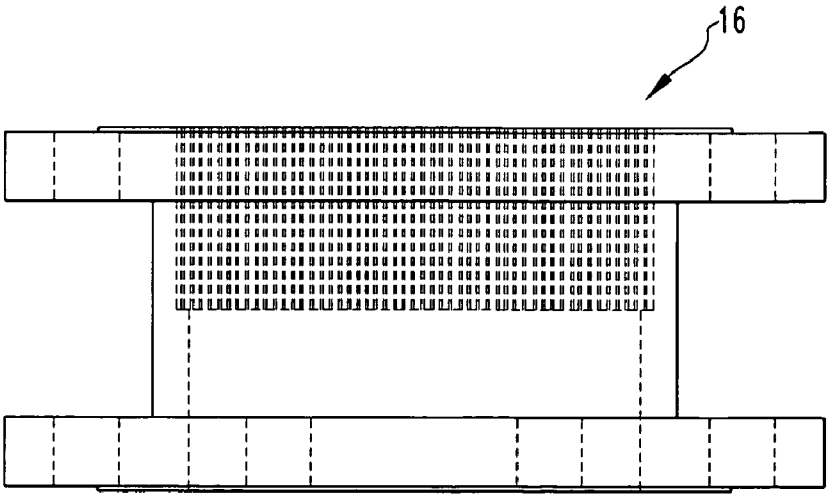


FIG.1B

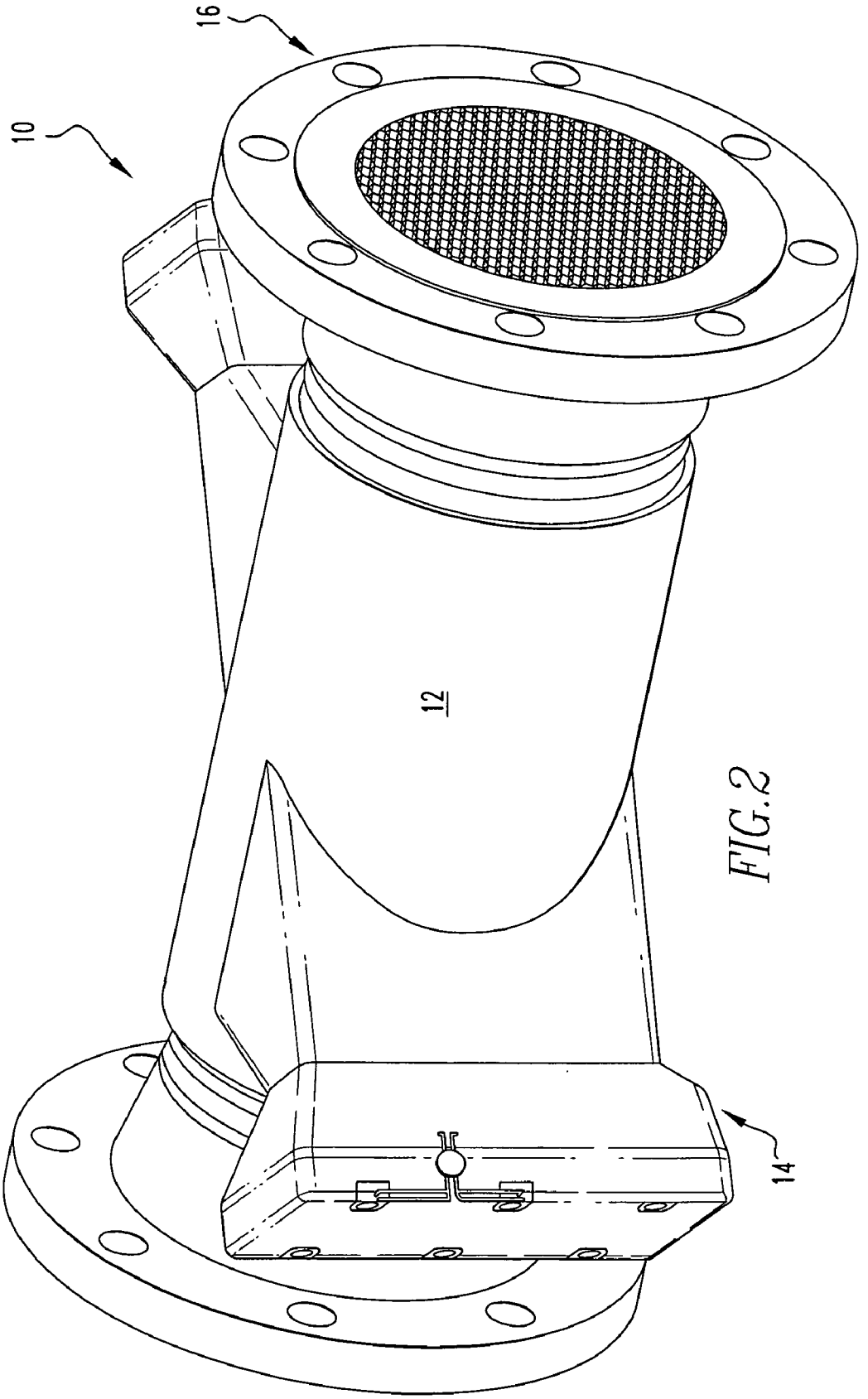


FIG.2

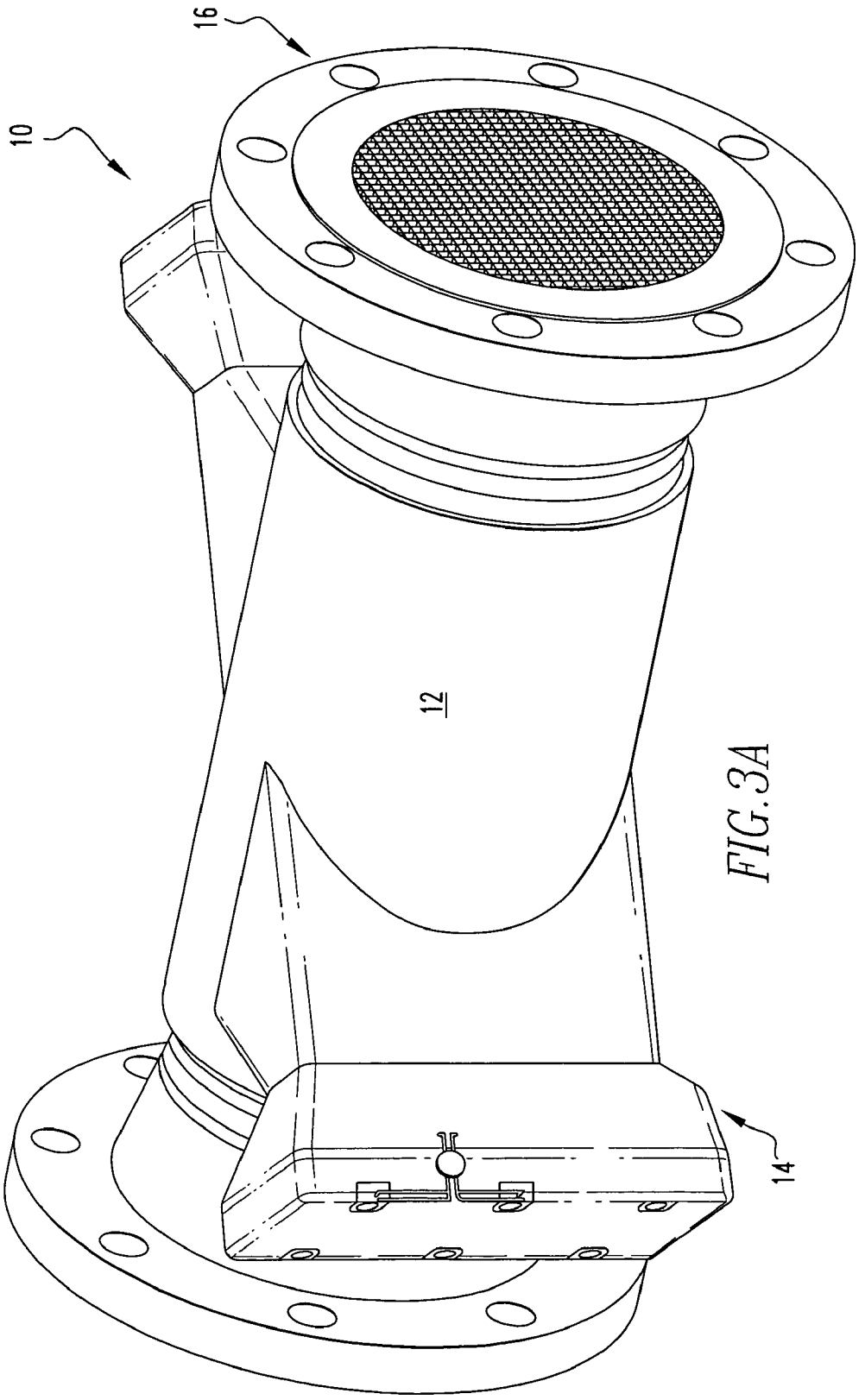


FIG. 3A

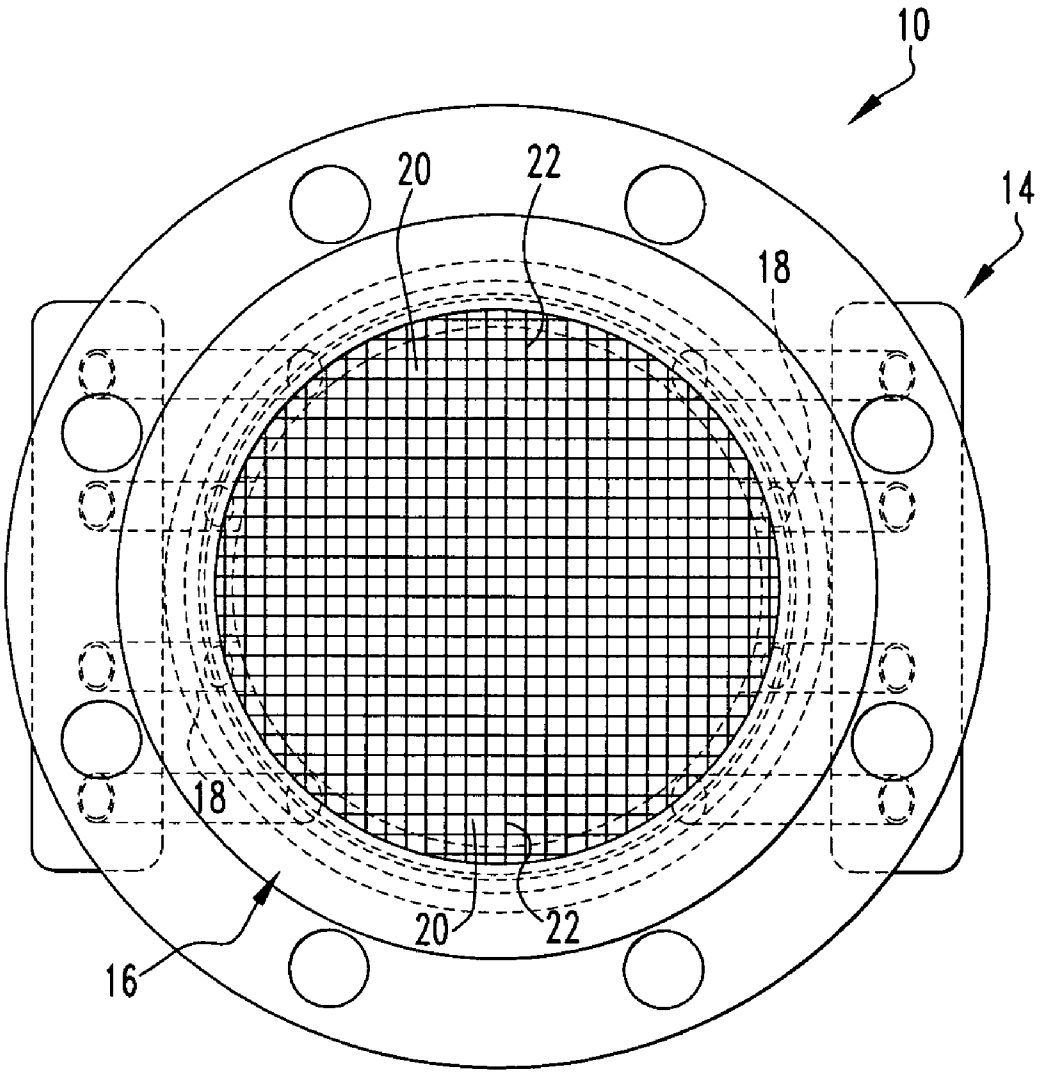


FIG.3B

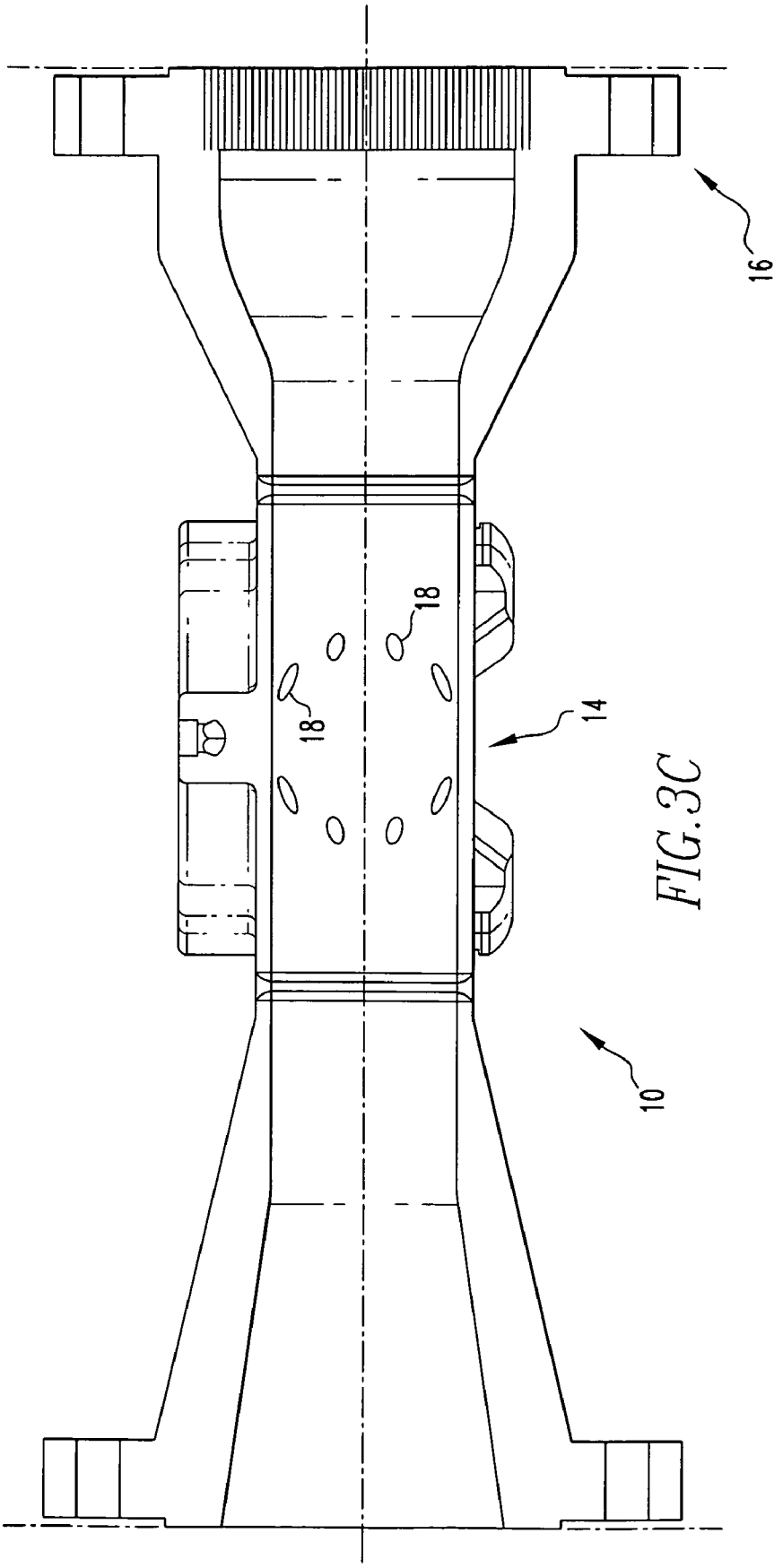


FIG. 3C

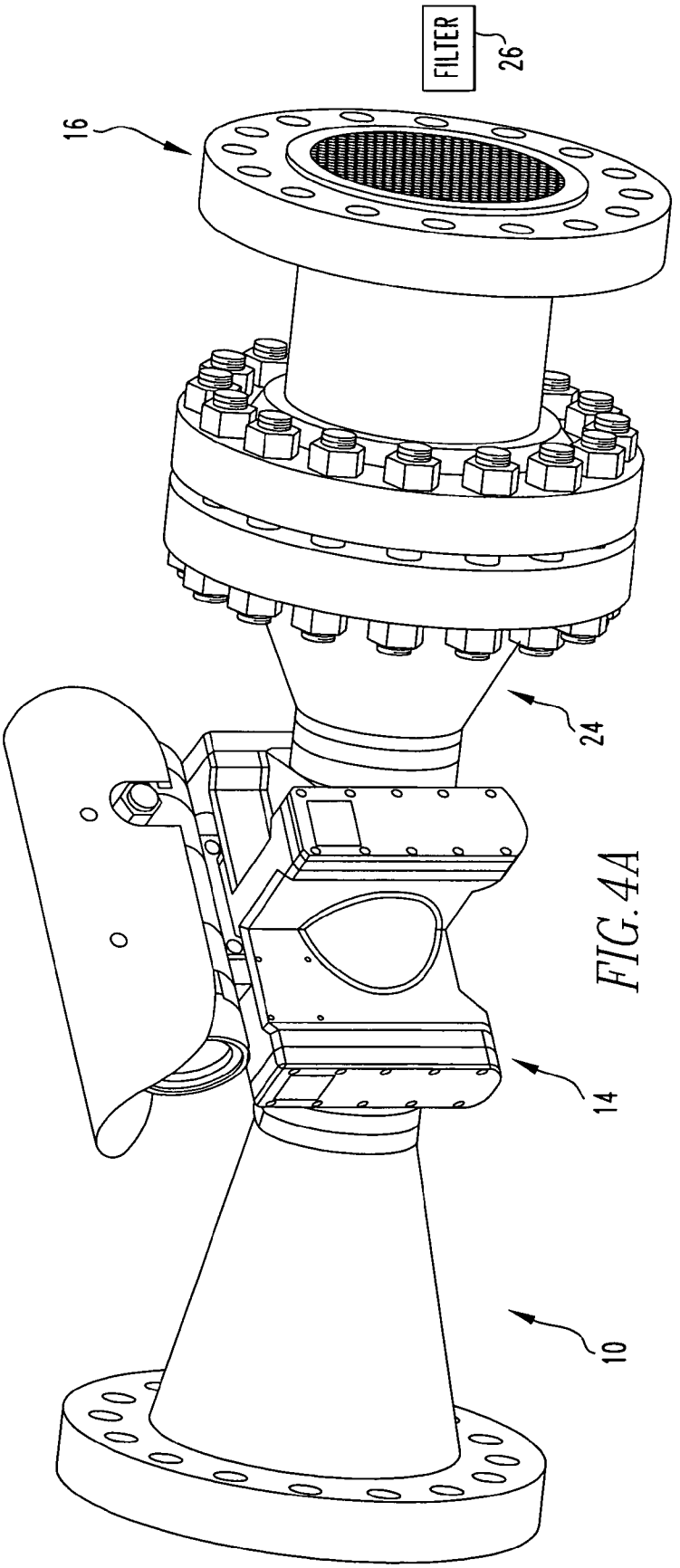


FIG. 4A

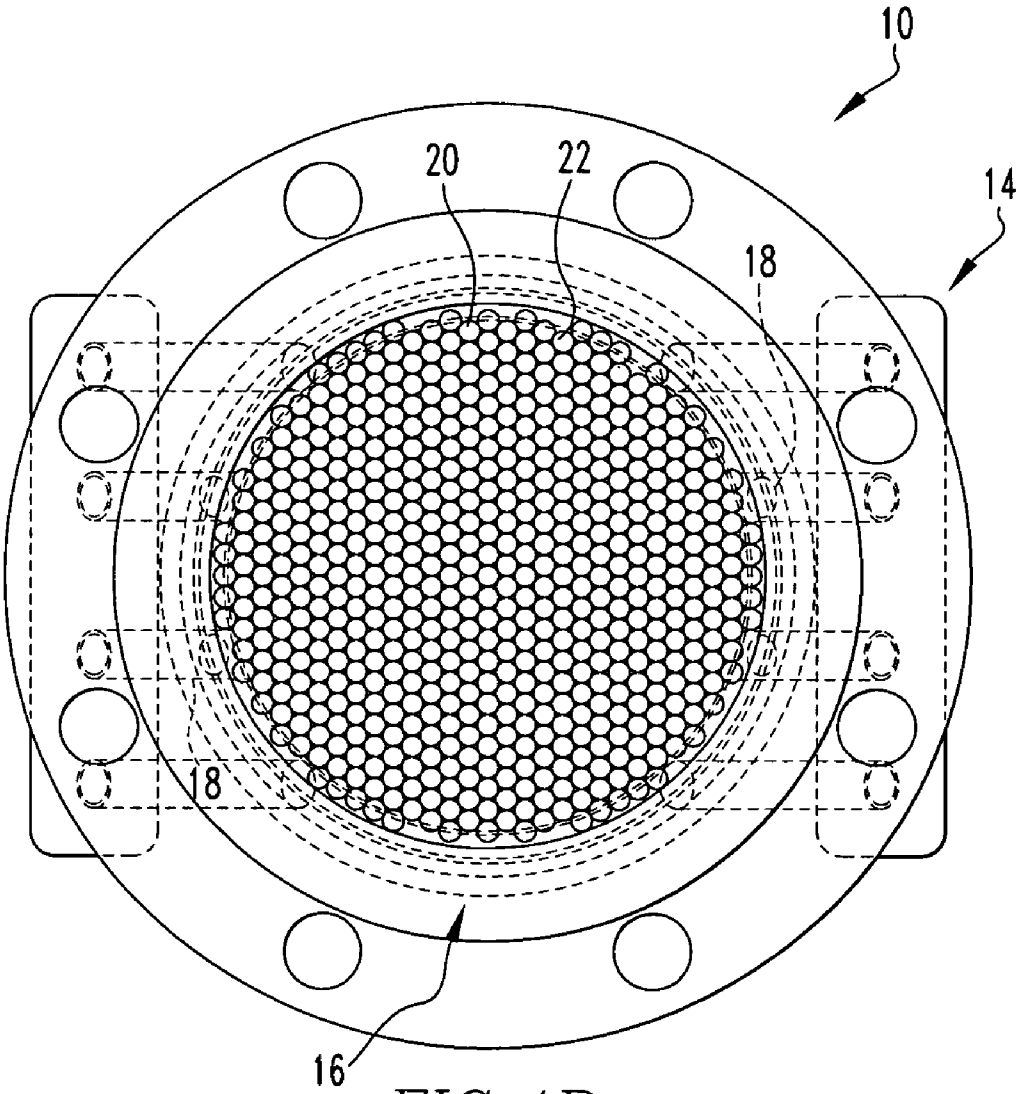


FIG. 4B

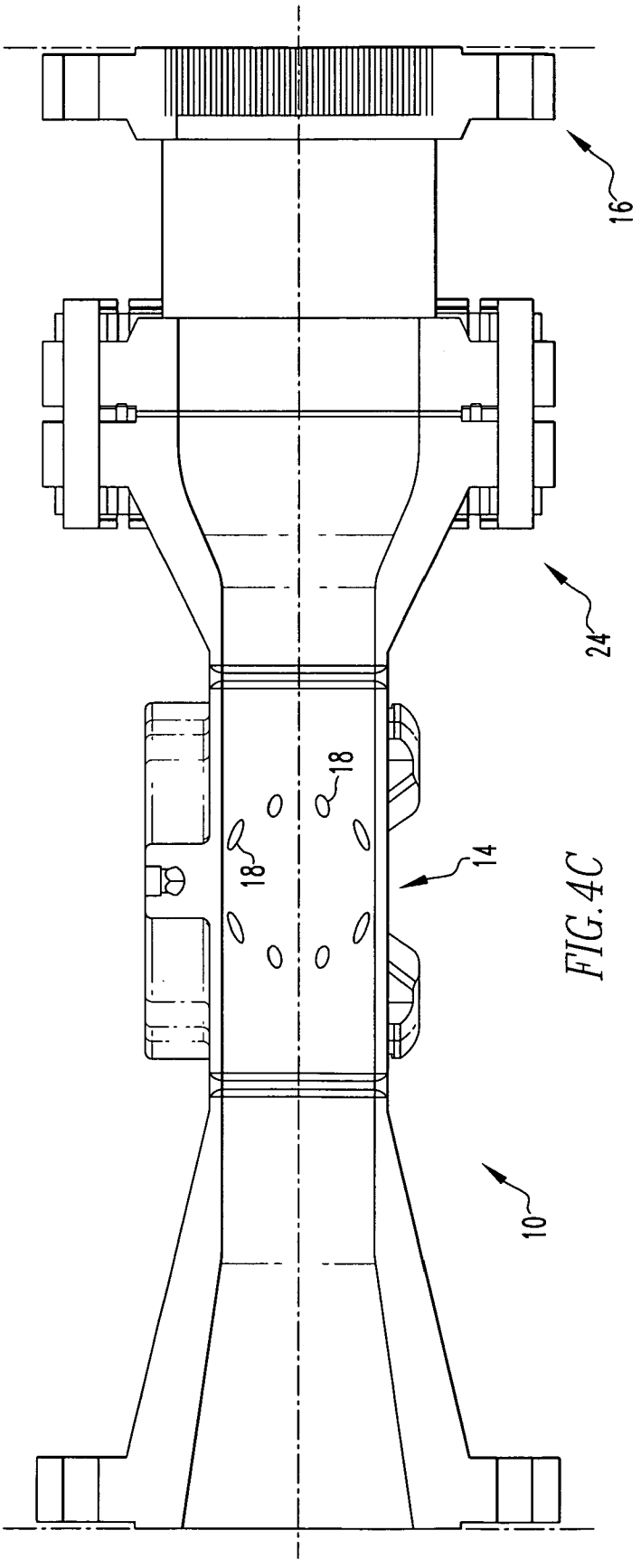


FIG. 4C

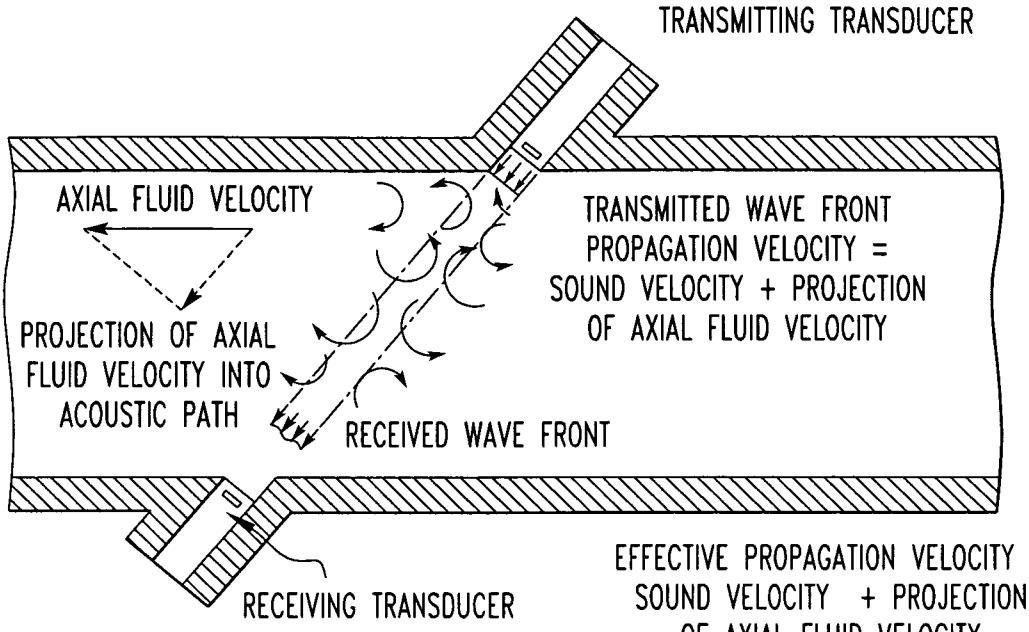

TRANSMITTING TRANSDUCER
AXIAL FLUID VELOCITY
TRANSMITTED WAVE FRONT PROPAGATION VELOCITY = SOUND VELOCITY + PROJECTION OF AXIAL FLUID VELOCITY
PROJECTION OF AXIAL FLUID VELOCITY INTO ACOUSTIC PATH
RECEIVED WAVE FRONT
RECEIVING TRANSDUCER
EFFECTIVE PROPAGATION VELOCITY = SOUND VELOCITY + PROJECTION OF AXIAL FLUID VELOCITY ± NET VELOCITY CONTROL BUTTON OF TURBULENT EDDIES

FIG. 5A

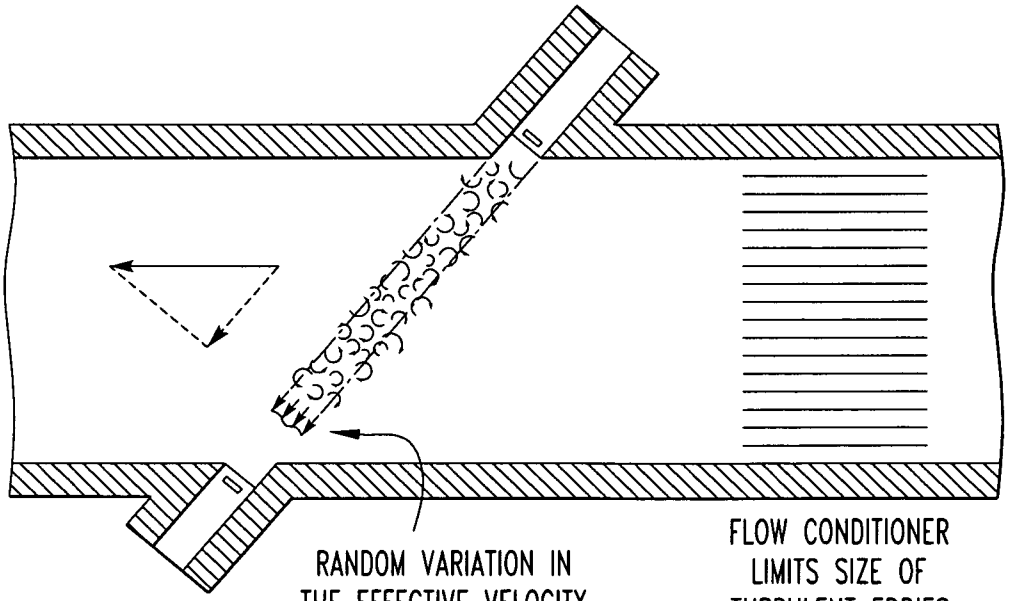

RANDOM VARIATION IN THE EFFECTIVE VELOCITY OF THE RECEIVED WAVE FRONT MUCH REDUCED BECAUSE EDDY VELOCITIES ARE AVERAGED WITHIN THE ACOUSTIC BEAM
FLOW CONDITIONER LIMITS SIZE OF TURBULENT EDDIES

FIG. 5B

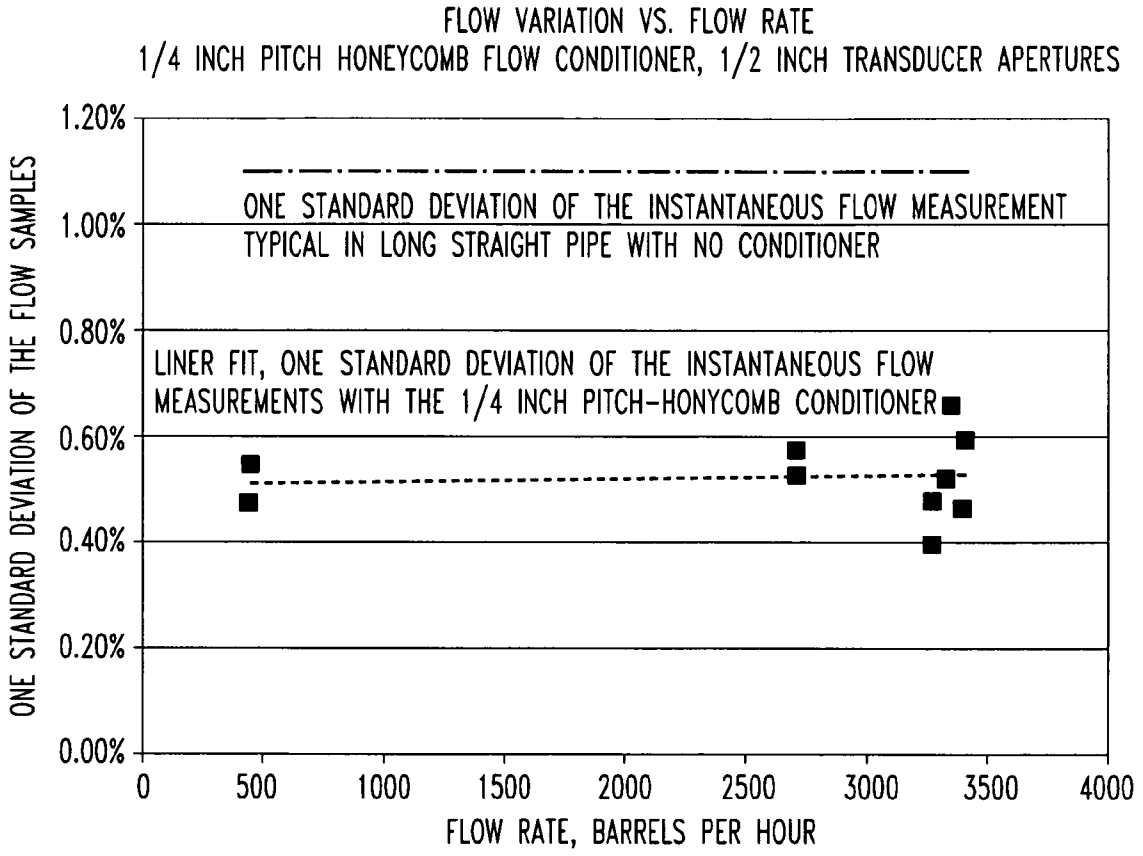

FLOW VARIATION VS. FLOW RATE
1/4 INCH PITCH HONEYCOMB FLOW CONDITIONER, 1/2 INCH TRANSDUCER APERTURES
ONE STANDARD DEVIATION OF THE FLOW SAMPLES
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
ONE STANDARD DEVIATION OF THE INSTANTANEOUS FLOW MEASUREMENT
TYPICAL IN LONG STRAIGHT PIPE WITH NO CONDITIONER
LINER FIT, ONE STANDARD DEVIATION OF THE INSTANTANEOUS FLOW
MEASUREMENTS WITH THE 1/4 INCH PITCH-HONYCOMB CONDITIONER
0
500
1000
1500
2000
2500
3000
3500
4000
FLOW RATE, BARRELS PER HOUR

FIG. 6

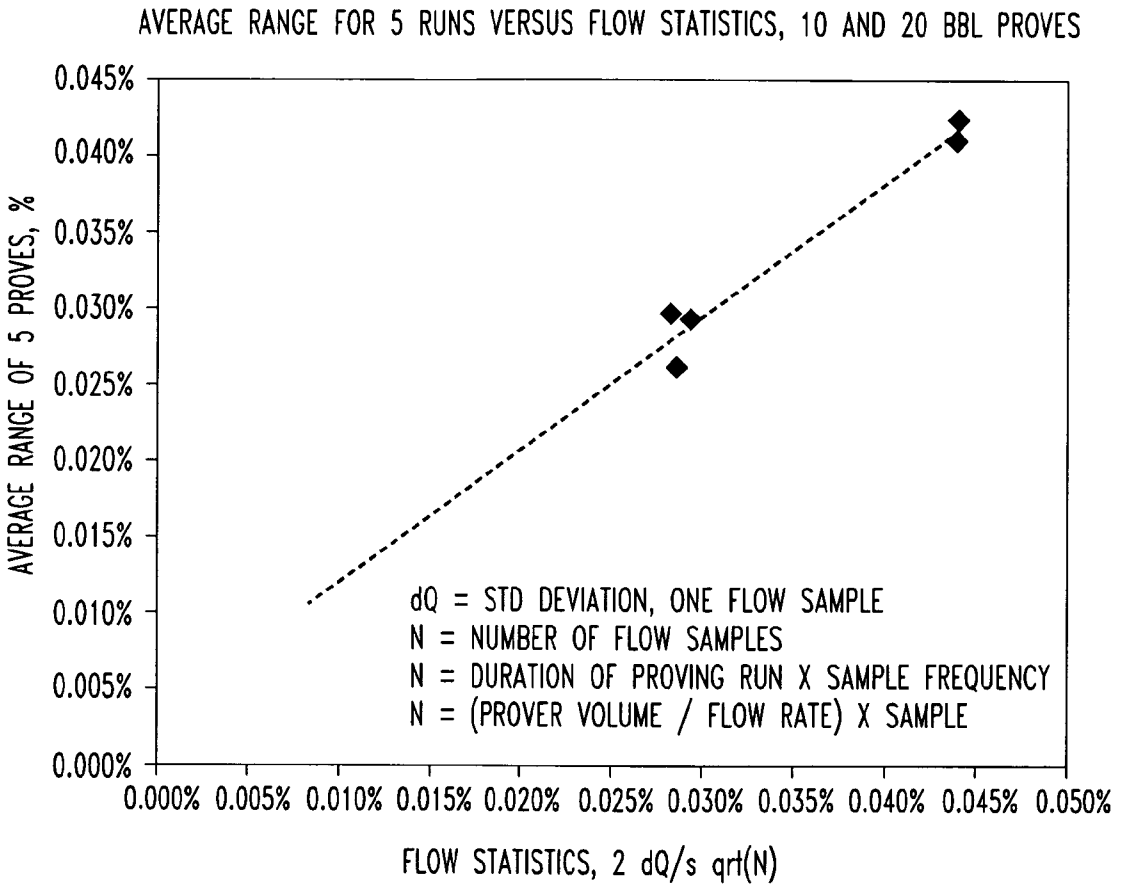

AVERAGE RANGE FOR 5 RUNS VERSUS FLOW STATISTICS, 10 AND 20 BBL PROVES
AVERAGE RANGE OF 5 PROVES, %
0.045%
0.040%
0.035%
0.030%
0.025%
0.020%
0.015%
0.010%
0.005%
0.000%
0.000% 0.005% 0.010% 0.015% 0.020% 0.025% 0.030% 0.035% 0.040% 0.045% 0.050%
FLOW STATISTICS, 2 dQ/s qrt(N)
dQ = STD DEVIATION, ONE FLOW SAMPLE
N = NUMBER OF FLOW SAMPLES
N = DURATION OF PROVING RUN X SAMPLE FREQUENCY
N = (PROVER VOLUME / FLOW RATE) X SAMPLE

FIG. 7

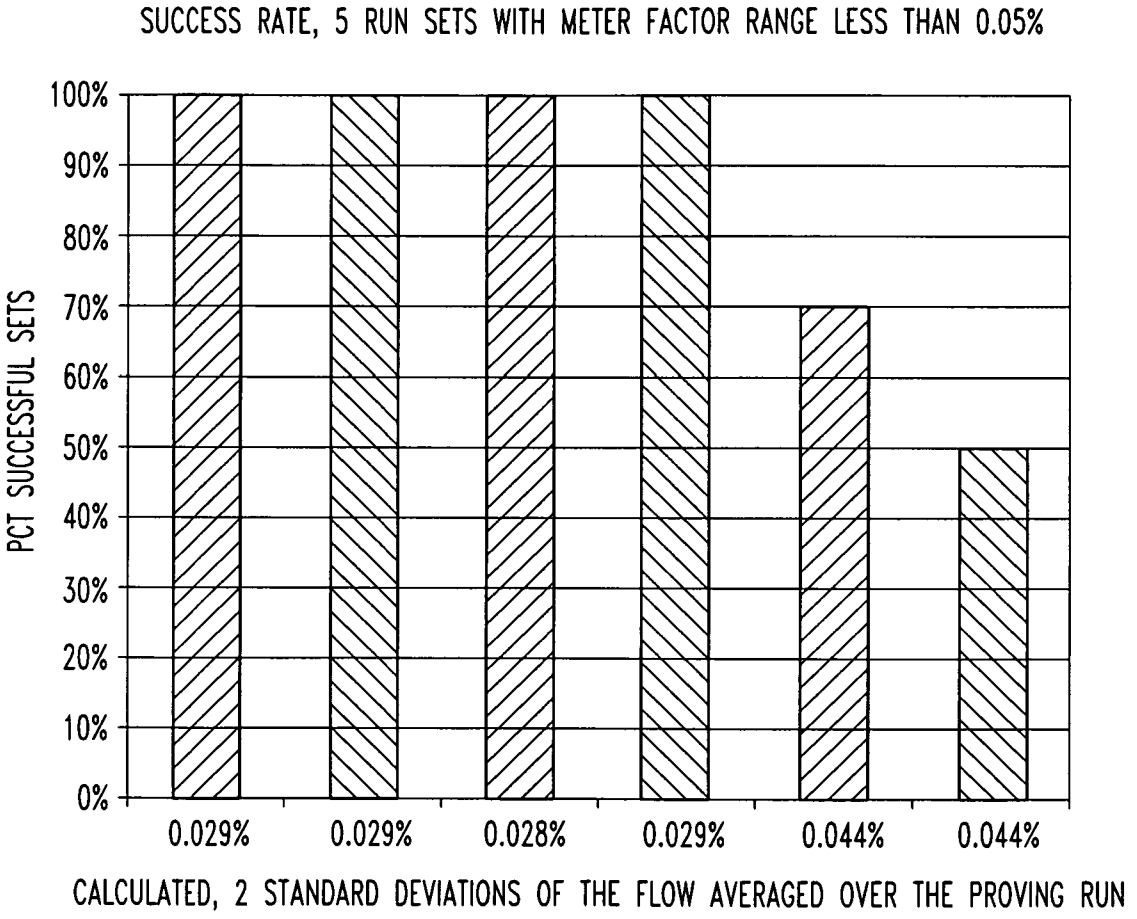

SUCCESS RATE, 5 RUN SETS WITH METER FACTOR RANGE LESS THAN 0.05%
PCT SUCCESSFUL SETS
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.029%
0.029%
0.028%
0.029%
0.044%
0.044%
CALCULATED, 2 STANDARD DEVIATIONS OF THE FLOW AVERAGED OVER THE PROVING RUN

FIG.8

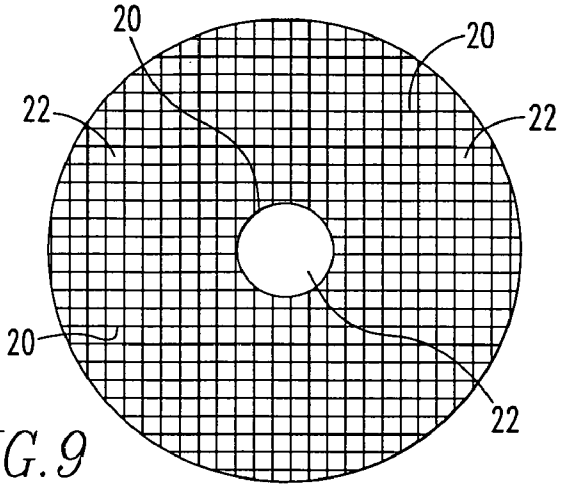


FIG. 9

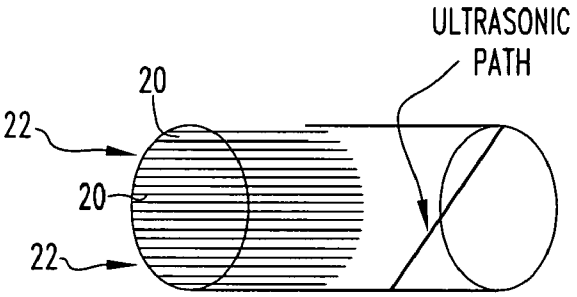


FIG. 10

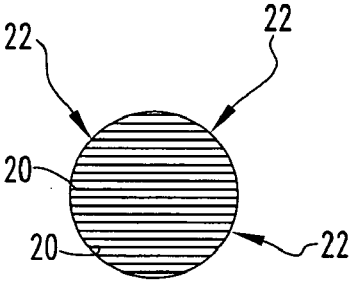


FIG. 11

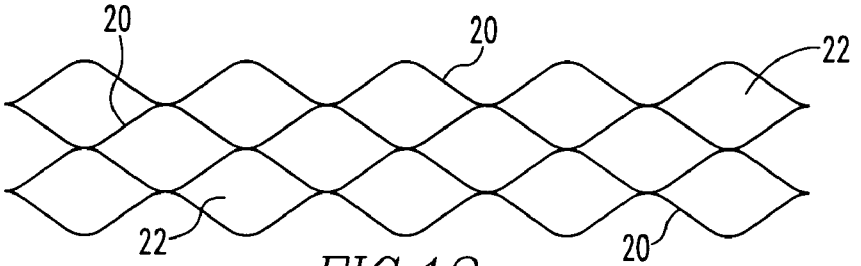


FIG. 12

METHOD FOR PRODUCING A TURBULENCE CONDITIONER FOR USE WITH AN ULTRASONIC FLOW METER IN A PIPE

CROSS-REFERENCE TO RELATED APPLICATIONS

This is a divisional application of U.S. patent application Ser. No. 12/002,270 filed Dec. 14, 2007 now U.S. Pat. No. 7,823,462.

FIELD OF THE INVENTION

The present invention is related to the altering of the structure of turbulence in a pipe such that the turbulent variations of the fluid velocity, as measured by a transit time ultrasonic flow meter downstream of a turbulence conditioner, are much reduced. (As used herein, references to the "present invention" or "invention" relate to exemplary embodiments and not necessarily to every embodiment encompassed by the appended claims.) The reduction in turbulent velocity variations facilitates the "proving" of the ultrasonic meter—confirming its calibration against a standard—making it possible to confirm this calibration with significantly fewer runs of the prover than is possible with the same ultrasonic meter and the same prover operating without the turbulence conditioner.

BACKGROUND OF THE INVENTION

This section is intended to introduce the reader to various aspects of the art that may be related to various aspects of the present invention. The following discussion is intended to provide information to facilitate a better understanding of the present invention. Accordingly, it should be understood that statements in the following discussion are to be read in this light, and not as admissions of prior art.

Transit time ultrasonic flowmeters have exhibited excellent repeatability and absolute accuracy in many flow measurement applications. However, characteristics inherent in the nature of their measurements present difficulties when these meters are applied to custody transfer measurements of petroleum products. A custody transfer takes place when ownership of a batch of a particular product changes. On a small scale, such a transfer takes place at the pump in a gas station, between the owner of the gas station and his customer.

It is industry practice in custody transfer measurements to "prove" the meter; that is, to establish its calibration accurately, by independent means. Provers are usually devices of fixed and precisely established volume. The time required to deliver the volume of product defined by the prover is accurately defined by the transit of a ball or piston, pushed by the product, from one end of the prover to the other. High speed diverter valves initiate the prover run and bypass the prover when the ball reaches the end of its travel. Position switches at the beginning and end of the prover synchronize the proving operation with the operation of the custody transfer meter—the meter to be used to measure the amount of product delivered to a specific customer. The volumetric output measured by the custody transfer meter (in traditional practice, a turbine or positive displacement meter) during the proving run is compared to the volume of the prover and a meter factor (i.e., a calibration correction) is established.

It is also industry practice to perform a set of several prover runs—five is typical—to establish the "repeatability" of the meter factor of the custody transfer meter. Repeatability in the petroleum industry is usually defined as follows: the difference between the high and low meter factors from a set of prover runs, divided by the low meter factor from that set. The repeatability (or in statistical terminology, "range") of a set of proving runs is a measure of the uncertainty of the meter factor as determined by the average of the results of that set of runs. For example, a repeatability of 0.05% in 5 runs of the prover indicates that the true meter factor for the custody transfer meter lies within a ±0.027% band of the mean meter factor from that run set, with 95% confidence. A meter factor of this accuracy is the accepted standard for custody transfer measurement.

Unlike turbine and positive displacement flow meters, a transit time ultrasonic flow meter does not measure volumetric flow rate continuously, but instead infers it from multiple samples of fluid velocity. Specifically, the volumetric flow rate is determined from periodic measurements of the axial fluid velocity as projected onto one or more acoustic paths—paths along which the transit times of pulses of ultrasound are measured. The path velocity measurements are combined according to rules appropriate to their number and location in the pipe. Many meters employ parallel chordal paths arranged in accordance with a specific method of numerical integration.

The period over which an ultrasonic transit time meter collects a single set of velocity measurements (one velocity measurement or more, depending on the number of paths) is determined by the path transit times, the number of paths, and the data processing capabilities of the meter itself. For liquid meters, the flow samples will typically be collected over periods ranging from 5 to 100 milliseconds, resulting in sample frequencies between 10 Hz and 200 Hz. These figures may differ from one ultrasonic meter design to another.

An ultrasonic flow measurement is thus a sample data system on two counts:

(1) It does not measure the velocity everywhere across the pipe cross section but only along the acoustic paths, and

(2) It does not measure velocity continuously, but instead takes a series of "snapshots" of the velocity from which it determines an average.

Because of these properties, a transit time ultrasonic meter responds to flow phenomena like turbulence differently than other meters commonly used for custody transfer in the petroleum industry. More specifically, the individual flow measurements of transit time ultrasonic meters will be affected by the small scale random (i.e., turbulent) variations in local fluid velocity. These variations are both temporal and spatial, and an ultrasonic instrument must make multiple measurements to determine the true average flow rate—to reduce the random error contributions due to turbulence to acceptable levels. Turbine meters and positive displacement meters, on the other hand, respond to the flow field in the pipe as a whole; integration of the fluid velocity in space and time is inherent in the nature of their responses. On the other side of the ledger, transit time ultrasonic meters are not encumbered by physical limitations like bypass leakage and friction, and may therefore provide measurement capability over a wider range of velocity and viscosity conditions.

For custody transfer, flow meters are designed to produce pulses per unit volume of fluid that passes through them (for example, 1000 pulses/barrel). The meter factor MF is given by:

$$MF = V/NP$$

Here

V is the volume of the standard—the prover—between the two position switches embedded in its walls. When a proving run is initiated the flowing fluid is diverted

through the prover and pushes a ball or piston past the upstream switch, initiating the run, which is terminated when the ball or piston reaches the downstream switch

NP is the number of pulses produced by the meter during the period which begins when the upstream switch is actuated (time T1) and ends when the downstream switch is actuated (time T2).

Ultrasonic meters determine a flow rate Q in volume units per second from individual measurements of fluid velocity along one or more acoustic paths. They therefore must generate pulses by means of a frequency converter that produces pulses at a rate k exactly proportional to the volumetric flow rate. Thus the number of pulses NP is given by:

$$NP=kQ(T2-T1)$$

If the uncertainties in the volume of the standard, the frequency converter k, and the actuations of the upstream and downstream switches are ignored (these terms are generally smaller by an order of magnitude than the uncertainties associated with the flow instrument calibration. In more detailed analyses they are not ignored), the per unit uncertainty in meter factor for a 95% confidence level is given by:

$$dMF/MF=2dQ(N)/Q=2\sigma_{mean}(N)$$

Where dQ(N) is one standard deviation of the mean of the N flow samples collected during the prove, or $\sigma_{mean}(N)$.

One standard deviation of the mean, $\sigma_{mean}(N)$, of N representative flow samples taken during a proving run is given by:

$$\sigma_{mean}(N)=S/(N)^{1/2}$$

Here, S is the standard deviation of the population of flow samples—the quantitative characterization of the random variability, produced by the turbulence, in the individual flow measurements of the ultrasonic meter, from one flow sample to the next.

An examination of the above equation reveals the variables that must be controlled to achieve satisfactory proving performance in ultrasonic meters: the turbulence intensity as it affects the standard deviation of the flow samples, S, in combination with the number of samples, N, accumulated during each proving run. These parameters must be such that σ_{mean} (N) is small enough to ensure that the range of measured meter factors does not exceed the requirement. Calculations indicate that, if $\sigma_{mean}(N)$ can be made small, meters will prove successfully more than 99% of the time.

Meeting these requirements is not straightforward. With a typical line prover operating at nominal flow rate, the duration of a single proving run is about 20 seconds, more or less. If a sample frequency of 50 Hz is assumed, the number of samples that will be collected during a proving run is 20×50=1000. As noted in the previously referenced patent, the random variations due to turbulence in the flow measurements of a four path chordal ultrasonic can be in the 1.75% range (one standard deviation or S) though upstream piping can lead to variations as low as 1.2% or as high as 3%. Substituting the 1.2% figure, 20 second proving runs will produce a $\sigma_{mean}(N)$ of about 0.04%. With the this value of $\sigma_{mean}(N)$, the probability of obtaining a set of 5 proving runs within a 0.05% range is less than 40%, a figure essentially consistent with actual proving experience. Experience also confirms what calculations show: Higher turbulence will produce still smaller probabilities of success.

This, then, is the problem. Turbulence, such as normally encountered in petroleum product pipelines, adversely affects the repeatability of the meter factors for transit time ultrasonic flowmeters, as measured in short duration prover runs. Unless something is done to alter the character of the turbulence, it appears that ultrasonic flowmeter meter factors measured with conventional provers will not achieve repeatability figures meeting petroleum industry expectations.

U.S. Pat. No. 6,647,806 is based on the hypothesis put forward by Dryden. (Hugh L. Dryden and G. B. Schubauer, *The Use of Damping Screens for the Reduction of Wind Tunnel Turbulence*, Journal of Aeronautical Science, April 1947.) He tied the reduction in turbulence produced by a series of one or more fine mesh screens in cascade to the production of eddies of very small diameters whose energy was dissipated as heat in a settling chamber downstream of the screen(s). Because screens are structurally impractical for resisting the hydraulic forces produced by liquid flow, the means proposed by the patent endeavored to produce the same effect with relatively small holes in plates. It will be seen in the data of Table 1 of that patent, reproduced below, that the improvements achieved were small. The largest reductions in turbulent variations cited in the prior patent were produced by reducers, either alone, or in combination with plates having small holes.

TABLE 1

Reproduced from U.S. Pat. No. 6,647,806 B1

Turbulence conditioner Configuration	Standard Deviation of One Flow Sample
Straight pipe with no diffuser mechanism	1.2% to 1.75%*
Large hole perforated plate	1.61%
Small hole perforated plate	0.93%
Reducer immediately upstream	0.63%
Reducer/large hole perforated plate	0.64%
Reducer/small hole perforated plate	0.59%

*The lower figure was not included in the referenced patent, but reflects multiple measurements made subsequent to the filing of that patent. Standard deviations higher than 1.75% can be found 5 to 10 diameters downstream of hydraulic disturbances such as bends, compound bends, and header exits.

The method for reducing the effects of turbulence employed by the turbulence conditioners of this invention does not rely on the elimination of turbulence through the dissipation of very small eddies. Rather, the reduction in the random deviations of flow samples is brought about reducing the eddy sizes such that they are effectively averaged within the acoustic beams of the ultrasonic meter.

The reduction in eddy sizes produced by the turbulence conditioners of this invention also leads to an increase in the frequencies of the random variations in fluid velocity produced by the turbulence. The frequency increases also lead to improved proving performance, by making a limited sample of N velocity measurements collected during a proving run more representative of the entire population of velocity variations.

SUMMARY OF THE INVENTION

The present invention pertains to an apparatus for determining fluid flow in a pipe. The apparatus comprises an ultrasonic flowmeter which communicates with the interior of the pipe through at least one pair of apertures, where each aperture of the one pair of apertures has an effective diameter. The apparatus comprises a turbulence conditioner disposed in the pipe having openings where the pitch between openings is a function of the effective diameter of the apertures.

The present invention pertains to a turbulence conditioner for a pipe. The conditioner has openings and a pitch. The conditioner has walls between the openings whose thickness is a function of the pitch. The conditioner has a length which is a function of the pitch.

The present invention pertains to a method for determining fluid flow in a pipe. The method comprises the steps of flowing fluid through a turbulence conditioner disposed in the pipe having openings where the pitch between openings is made a function of an effective diameter of an aperture of an ultrasonic flowmeter which communicates with the interior of the pipe through the aperture. There is the step of measuring the flow with the meter.

The present invention pertains to a method for producing a turbulence conditioner for use with an ultrasonic flow meter in a pipe. The method comprises the steps of identifying an effective diameter of an aperture in the pipe through which the flowmeter communicates with the interior of the pipe. There is the step of determining a pitch between holes in the conditioner as a function of the effective diameter.

The present invention pertains to an apparatus for determining fluid flow in a pipe, comprising an ultrasonic transit time flowmeter and a turbulence-altering turbulence conditioner, both placed in the pipe. The alteration of the turbulence by the apparatus is such that a meter calibration meeting very narrow accuracy requirements can be determined in a few runs of a prover (a volumetric standard), a capability not otherwise achievable. Several turbulence conditioner configurations that will produce the necessary alteration to the turbulence are described. A second arrangement of the apparatus is also described. It draws on a configuration employing a reducing nozzle downstream of the turbulence conditioner but upstream of the meter.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a honeycomb conditioner viewed from upstream with transducer apertures of chordal meter shown in phantom downstream.

FIG. **1**B is sectional view of the honeycomb conditioner (the chordal meter is not shown but couples to lower flange).

FIG. **2** is a perspective drawing of the honeycomb turbulence conditioner also as prescribed herein, with the chordal ultrasonic meter downstream.

FIG. **3**A is a perspective drawing of an "egg-crate" turbulence conditioner also as prescribed herein, with the chordal ultrasonic meter downstream.

FIG. **3**B is a sectional view of the "egg-crate" turbulence conditioner.

FIG. **3**C is a side sectional view of the "egg-crate" turbulence conditioner.

FIG. **4**A is a perspective drawing of a "mini-tube" turbulence conditioner also as prescribed herein, with a reducing nozzle and chordal meter downstream (and an expanding nozzle downstream of the meter, to maintain upstream and downstream pipe diameter).

FIG. **4**B is a sectional view of the "mini-tube" turbulence conditioner.

FIG. **4**C is a side sectional view of the "egg-crate" turbulence conditioner.

FIG. **5** is a sketch showing turbulent eddies intersecting an ultrasonic beam, (a) without a turbulence conditioner and (b) with the turbulence conditioners of this invention.

FIG. **6** is a plot of experimental results obtained with the honeycomb turbulence conditioner and flowmeter as described herein, showing the magnitude of the flow variations, as measured by one standard deviation of the flow samples, as a function of flow rate. The magnitude of variations that would typically be obtained without the turbulence conditioner is also shown.

FIG. **7** is a plot of experimental results, showing the average range of a set of five meter factor measurements obtained with the honeycomb turbulence conditioner and ultrasonic flowmeter as described herein, as a function of the calculated standard deviation of the mean flow during a proving run, for proving volumes typical of the flow rates present during the measurements.

FIG. **8** is a bar chart of experimental results showing the percentage of successful sets of 5 proving runs each, as a function of the calculated standard deviation of the mean flow during the proving runs.

FIG. **9** is a cross-section of a conditioner with different sized holes.

FIGS. **10** and **11** show a conditioner where the holes are not of equal dimensions.

FIG. **12** is a cross-section of a conditioner with holes having 2 sides.

DETAILED DESCRIPTION

Referring now to the drawings wherein like reference numerals refer to similar or identical parts throughout the several views, and more specifically to FIGS. **1**A, **1**B, **2**, **3**A, **3**B, **3**C, **4**A, **4**B and **4**C thereof, there is shown an exemplary apparatus **10** for determining fluid flow in a pipe **12**. The apparatus **10** comprises an ultrasonic flowmeter **14** which communicates with the interior of the pipe **12** through at least one pair of apertures **18**, where each aperture **18** of the one pair of apertures **18** has an effective diameter. The apparatus **10** comprises a turbulence conditioner **16** disposed in the pipe **12** having openings **22** where the pitch between openings **22** is a function of the effective diameter of the aperture **18**.

The conditioner **16** has walls **20** between the openings **22** whose thickness can be a function of the pitch. The conditioner **16** has a length which can be a function of the pitch. The meter **14** can be disposed up to 3 internal pipe **12** diameters downstream of the conditioner **16**. The pitch can be less than the effective diameter of the aperture **18**. The walls **20** can have a thickness between ¼ and 1/10 of the pitch. The length can be 5 to 20 times the pitch. The pitch can be a function of the meter's **14** diameter. The pitch can be a function of the meter's **14** maximum velocity. The pitch can be a function of the meter's **14** sampling rate.

The holes can have a cross-section that is two or more sided. FIG. **12** shows holes that are two sided. Alternatively, the holes can have a circular cross-section, as shown in FIGS. **4***a* and **4***b*. A filter **26** can be disposed in the pipe **12** upstream from the conditioner **16**. A nozzle **24** can be disposed in the pipe **12** upstream of the flowmeter **14** and downstream of the conditioner **16**. The meter **14** and the conditioner **16** can satisfy proving requirements for maximum and minimum flow velocities for which the meter is designed. The conditioner **16** and the meter **14** can satisfy a proving requirement of +/−0.027% uncertainty in five proving runs.

The present invention pertains to a turbulence conditioner **16** for a pipe **12**, as shown in FIGS. **1**A, **1**B, **2**, **3**A, **3**B, **3**C, **4**A, **4**B and **4**C. The conditioner **16** has openings **22** and a pitch. The conditioner **16** has walls **20** between the openings **22** whose thickness is a function of the pitch. The conditioner **16** has a length which is a function of the pitch.

The present invention pertains to a method for determining fluid flow in a pipe **12**. The method comprises the steps of flowing fluid through a turbulence conditioner **16** disposed in the pipe **12** having openings **22** where the pitch between openings **22**, is made a function of an effective diameter of an aperture **18** of an ultrasonic flowmeter **14** which communicates with the interior of the pipe **12** through the aperture **18**. There is the step of measuring the flow with the meter **14**.

The flowing fluid through a turbulence conditioner **16** step can include the step of flowing the fluid through the turbulence conditioner **16** wherein the conditioner **16** has walls **20** between the openings **22** whose thickness is made a function of the pitch. The flowing fluid through a turbulence conditioner **16** step can include the step of flowing the fluid through the turbulence conditioner **16** wherein the conditioner **16** has a length which is made a function of the pitch. The flowing fluid through a turbulence conditioner **16** step can include the step of flowing the fluid through the turbulence conditioner **16** disposed up to 3 internal pipe **12** diameters upstream of the conditioner **16**.

The flowing fluid through a turbulence conditioner **16** step can include the step of flowing the fluid through the turbulence conditioner **16** wherein the pitch is less than the effective diameter of the aperture **18**. The flowing fluid through a turbulence conditioner **16** step can include the step of flowing the fluid through the turbulence conditioner **16** wherein the walls **20** have a thickness between ¼ to 1/10 of the pitch. The flowing fluid through a turbulence conditioner **16** step can include the step of flowing the fluid through the turbulence conditioner **16** wherein the length of the conditioner **16** is 5 to 20 times the pitch.

The flowing fluid through a turbulence conditioner **16** step can include the step of flowing the fluid through the turbulence conditioner **16** wherein the holes have a cross-section that is two or more sided. Alternatively, the flowing fluid through a turbulence conditioner **16** step includes the step of flowing the fluid through the turbulence conditioner **16** wherein the holes have a circular cross-section.

The flowing fluid through a turbulence conditioner **16** step can include the step of flowing the fluid through a filter **26** disposed in the pipe **12** upstream from the conditioner **16**. The flowing fluid through a turbulence conditioner **16** step can include the step of flowing the fluid through a nozzle **24** disposed in the pipe **12** upstream of the flowmeter **14** and downstream of the conditioner **16**. The measuring step can include the step of measuring the flow with the meter **14** which meets a proving requirement. The measuring step can include the step of measuring the flow with the meter **14** which meets the proving requirement of +/−0.027% uncertainty in five proving runs.

The present invention pertains to a method for producing a turbulence conditioner **16** for use with an ultrasonic flowmeter **14** in a pipe **12**. The method comprises the steps of identifying an effective diameter of an aperture in the pipe **12** through which the flowmeter **14** communicates with the interior of the pipe **12**. There is the step of determining a pitch between holes in the conditioner **16** as a function of the effective diameter.

There can be the step of determining a thickness of walls between the openings as a function of the pitch. There can be the step of determining a length of the conditioner **16** as a function of the pitch. There can be the step of building the conditioner **16** having the pitch, wall thickness and length determined in the determining steps. The building step could include fabricating the center portion **35** having the holes **22**, cutting it to length and diameter to meet the design parameters determined for the pitch, wall thickness and length, and attaching a flange **37** to the center portion **35** so it can be seated in the pipe **12**.

The present invention pertains to an apparatus **10** for determining fluid flow in a pipe **12**, comprising a turbulence-altering turbulence conditioner **16** and an ultrasonic transit time flowmeter **14**, both placed in the pipe **12**. The arrangement facilitates the "proving" of the ultrasonic meter **14** in a number of prover runs comparable to, or better than the number required by meters of competing technologies (turbine meters and positive displacement meters)—an accomplishment not possible with conventional arrangements of ultrasonic meters **14**. Several alternative configurations for the turbulence conditioner **16** are described. The turbulence conditioners **16** can also be applied to an alternative arrangement of the enclosing piping and ultrasonic meter **14** which has been described in the prior art, and in which a nozzle **24** type reducer is employed upstream of the ultrasonic meter **14** but downstream of the turbulence conditioner **16**, with proving results better than previously achieved with this arrangement.

FIGS. **1**A, **1**B and **2** show one of the several alternative turbulence conditioners **16** employed by this invention with a chordal ultrasonic meter **14** downstream, as prescribed by this invention. The configuration, referred to as a "honeycomb" having six sides, has been tested to demonstrate the capabilities of this invention. Results will be described in later paragraphs. The key dimensional requirements of this exemplary embodiment of the invention are as follows:

1. In the configuration shown, the pitch of the honeycomb turbulence conditioner **16**—the spacing between the centers of the openings **22**—is one-half the effective diameter of the apertures **18** of the ultrasonic meter **14** (¼ inch pitch vs. ½ inch aperture); although generally, the pitch should be less than the effective diameter of the aperture **18**. The aperture **18** diameter is equal to the diameter of the transducer assembly if the bores of the pipe **12** penetrations containing the ultrasonic transducer assemblies are equal or nearly equal to the diameters of the transducer assemblies. In some ultrasonic meter **14** designs, the minor diameter of the opening **22** in the internal wall **20** of the pipe **12** through which the ultrasonic energy passes is smaller than the diameter of the transducer assembly. In such cases, this minor diameter of the opening **22** is the effective diameter of the aperture **18**. Substantial reductions in flow variations have been obtained with the ¼ inch pitch to ½ inch aperture **18** ratio. However, even greater reductions may be obtained if the pitch to aperture **18** ratio is smaller than one-half.
2. The thickness of the walls **20** of the honeycomb is a small fraction of the pitch (in the order of 1/10). Calculations show that walls **20** that are thin relative to the pitch of the turbulence conditioner **16**—in the range of ¼ to 1/10 of the pitch—will provide adequate structural strength for the turbulence conditioner **16**. Because the walls **20** are thin, the eddies generated in their lee are of extremely small diameter—small enough not to impact the net statistics of the flow velocities measured by the ultrasonic meter **14** (because the eddies are very small relative to the diameter of the aperture **18**). In this regard the honeycomb configuration and the other turbulence conditioner **16** configurations covered in this invention are inherently superior to the plate conditioners **16** of the previously referenced patent, where the dimensions of the ligaments are in the same order as the holes.
3. The axial length of the turbulence conditioner **16** is in the range of 5 to 20 times the pitch. This length is sufficient to eliminate global vortices created by features of the piping upstream of the conditioner **16**, obviating the need for additional flow conditioning. Turbulence conditioners **16** employing large diameter tubes or plates with holes are normally provided for turbine and ultrasonic meters **14** to eliminate global vortices. With the proposed turbulence conditioners **16** these will not be necessary. The 5:1 to 20:1 length to pitch ratio also provides a configuration that is axially stiff, thereby

producing a structure that does not deflect significantly in the flow stream and that is strong enough to withstand flow forces. Calculated pressure drops of the turbulence conditioners **16** described herein are comparable to the pressure drops of conventional tube type flow conditioners. The pressure drops of the turbulence conditioners **16** described herein are less than the pressure drops of plate type turbulence conditioners **16** such as described in the previously referenced patent.

4. In FIG. **2**, the ultrasonic meter **14** is located approximately one internal pipe **12** diameter downstream of the turbulence conditioner **16**. Data discussed later show that marked improvements in proving performance are achieved with this configuration. A separation in the range of up to 3 internal pipe **12** diameters will produce satisfactory performance. Larger separation will allow eddies to agglomerate into larger eddies and new eddies to form, reducing the effectiveness of the acoustic beams of the ultrasonic meter **14** in averaging the rotational velocities of the turbulent eddies. Axial distances shorter than ½ diameter can cause local velocity profile perturbations produced or preserved by the turbulence conditioner **16** to be "seen" by the ultrasonic meter **14**, degrading its capability to integrate the axial velocity profile numerically.

FIGS. **3**A, **3**B, **3**C, **4**A, **4**B and **4**C show alternative configurations for turbulence conditioners **16** meeting the requirements prescribed above. For each design, the axial length of the conditioner **16** provides stiffness which reduces axial deflections and stresses to very small values provided the egg-crate of FIGS. **3**A, **3**B, and **3**C and the tube bundle of FIGS. **4**A, **4**B, **4**C can be made to act as a plate such that the tensile stresses on the downstream end can be transmitted from tube to tube. For the tube bundle design of FIGS. **4**A, **4**B, and **4**C, this is accomplished by redundant means:

(a) A shrink fit, produced by heating the enclosing pipe **12** 100° F. before inserting the bundled tubes, produces frictional forces between tubes capable of withstanding the hydraulic forces tending to dislodge them, and

(b) Spot welds between adjacent tubes near the downstream end of the bundle, ensures that the bundle acts as a single structure. Alternatively, the unions among tubes can be achieved by soldering.

Spot welds would also be used to stiffen the downstream corners of the egg-crate conditioner **16** of FIGS. **3**A and **3**B.

Because petroleum pipelines are not free of debris (for example precipitated wax or asphaltenes) and because of the relatively small openings **22** of the conditioners **16** prescribed in this invention, it is beneficial to install a basket type flow filter **26** or fine mesh strainer five or more diameters upstream of the turbulence conditioners **16** prescribed herein. The aggregate pressure loss generated by the filter **26** or strainer, the turbulence conditioner **16**, and the ultrasonic flowmeter **14** itself is less than that of competing technologies. A turbine meter **14** also benefits from a similar filter **26** and a flow conditioner having a similar pressure drop and itself generates a pressure drop, which the ultrasonic meter **14** does not. A positive displacement meter **14** also generally has a filter **26** and though it generally has no turbulence or flow conditioner, itself generates a pressure loss greater than that produced by the turbulence conditioners **16** described herein.

FIGS. **5**A and **5**B illustrate the principles of this invention. Transit time ultrasonic meters measure the travel times of pulses of ultrasonic energy transiting from a transmitting transducer to a receiving transducer. In the figures, a transmitting transducer has generated a pulse that is traveling diagonally across the flow stream in the direction of flow. The pulse's transit time is given by the quotient of the distance between transducers and the propagation velocity of the ultrasound. For a transmission in the direction shown in the figure, the propagation velocity is the sum of the velocity of ultrasound in the fluid at rest and the fluid velocity projected onto the acoustic path. When a second transmission is generated in the opposite direction (that is, from the downstream transducer in the figure to the upstream transducer) the propagation velocity is the difference between the velocity of ultrasound in the fluid at rest and the fluid velocity projected onto the acoustic path. Thus, knowing the path length, the two transit time measurements yield two equations in two unknowns: the ultrasound velocity in the fluid at rest and the fluid velocity projected onto the acoustic path. But, as illustrated in FIG. **5**A, the fluid velocity projected onto the acoustic path is determined not only by the projection of the average axial velocity (the variable that needs to be measured) but also the net projection from the multiple turbulent eddies that accelerate or retard the pulse on its way. The transmission in the opposite direction is also affected by the turbulence, but not generally by the same eddies (which may have moved on between transmissions). For the condition illustrated in FIG. **5**A, therefore, multiple measurements are needed to average out the effects of the turbulent eddies and thereby to determine the average axial fluid velocity along the path.

When the maximum eddy diameter is made significantly smaller than the diameter of the transducer apertures that form the acoustic paths along which the pulses of ultrasound travel, the disturbances to the ultrasound propagation velocity produced by the tangential velocity of an eddy tend to be canceled in each transmission. This is illustrated in FIG. **5**B. Within the beam of ultrasound, the component of an eddy that hastens the ultrasound transmission is offset by the component of the same eddy that retards it. Eddies typically move at a velocity close to the average fluid velocity—typically in the order of 100 inches/second. The propagation velocity of the ultrasound is in the order of 50,000 inches/second. Thus the displacement, during a pulse transit, of an eddy within the 0.7 inch projected axial width of a (typical) 0.5 inch ultrasonic transmission beam is negligibly small. Thus the rule is that the turbulence conditioner design should allow the passage of only those eddies which are significantly smaller than the aperture diameter and should break up larger eddies such that only eddies whose diameter is significantly smaller than the aperture are produced.

As noted above, in the present invention, the random deviations of flow samples of the ultrasonic meter **14** are made small by reducing the turbulent eddy sizes such that they are effectively averaged within the acoustic beams of the meter **14**. The data of FIG. **6** show the reduction produced by a ¼ inch honeycomb turbulence conditioner **16**, as shown in FIG. **1**, in a 6 inch duplex ultrasonic meter **14** (the duplex meter **14** consists of two essentially independent meters **14** of four paths each), having transducer apertures **18** of approximately ½ inch diameter. It will be seen that, over a 9:1 range of flows, the turbulence conditioner **16** produces standard deviations for individual flow samples of approximately ½% (versus a standard deviation of 1.2%, which would be expected from the same meter **14** operating in a straight pipe **12** without the turbulence conditioner **16**).

The reduction in the standard deviation in the flow samples translates into improved proving performance. The proving performance with the honeycomb conditioner **16** was measured by examining the range of meter **14** factors in sets of 5 proving runs each. Ten sets of 5 run trials were carried out for each of the two 4 path meters **14**, at two different flow rates and with two different proving volumes—a total of thirty 5

run sets for each of the two meters **14**. For twenty of these run sets a prover volume of 20 barrels was employed, 10 sets each at 3400 and 2700 barrels per hour respectively. For the remaining runs a prover volume of 10 barrels with a flow rate of 3400 barrels per hour was employed. Proving volumes in the 10 to 20 barrel range are typical for the two flow rates.

Proving data collected during the tests with the turbulence conditioner **16** of FIG. **1** are presented in FIG. **7**. The abscissa of FIG. **7** is the statistical characterization of the flow variability developed in a preceding section: $2\times\sigma_{mean}$, twice the quotient of the standard deviation of the individual flow samples measured during a proving run and the square root of the number of samples N taken during that run. N is computed as the product of the ultrasonic meter **14** sample rate (about 50 Hz) and the duration of the run. The ordinate of FIG. **7** is the average range of the proving runs. A linear trend of the data shows that the average range of the data from a set of 5 proving runs is approximately equal to $2\times\sigma_{mean}$.

This trend line can be used to project proving performance. If two standard deviations of the measurements are ±0.025%, a normal distribution shows that the odds that one run will fall outside a 0.05% band encompassing the mean are 1 in 20. The odds that any one of the remaining four runs will fall outside the opposite end of the band are 1 in 40. Thus the odds of obtaining two results differing by more than 0.05% are: $(1/20)\times(1/40)+(1/20)\times(1/40)+(1/20)\times(1/40)+(1/20)\times(1/40)=0.005$. With $2\times\sigma_{mean}=0.025\%$, sets of five proving runs should fall within the prescribed 0.05% range 99.5% of the time.

FIG. **8** shows the percentage of 5 run prove sets that were actually successful—that met the requirement of 0.05% range for 5 proves. As projected above, the figure shows that, when $2\times\sigma_{mean}$ is 0.025% or less, 100% of the 5 run sets were successful. When $2\times\sigma_{mean}$ is in the 0.045% range, about 50% to 70% of the 5 run sets are successful. These latter results are also roughly in accordance with statistical predictions.

The performance of FIGS. **7** and **8** is markedly better than would be obtained with the same chordal flowmeter **14** without the turbulence conditioner **16**. Without the conditioner **16**, $2\sigma_{mean}$ would be in the 0.06% range, at best, for the 20 barrel proves, implying a success rate of less than 50%, which is also in agreement with experience.

As has been previously noted, reducing nozzles **24**, such as described in the patent previously referenced (U.S. Pat. No. 6,647,806, incorporated in its entirety by reference herein), can be applied with the turbulence conditioners **16** described herein to enhance proving performance still further. FIG. **4** shows a tube bundle turbulence conditioner **16** meeting the dimensional parameters prescribed herein upstream of a reducing nozzle **24**, with an ultrasonic meter **14** downstream of the nozzle **24**. An expanding diffuser downstream of the meter **14** restores the upstream pipe **12** diameter at minimal loss. In the flow nozzle **24** configuration, the ultrasonic flow meter **14** is located in the cylindrical throat of the nozzle **24**, which increases the mean fluid velocity seen by the meter **14** as the reciprocal of the beta ratio squared. The beta ratio is the quotient of the nozzle **24** throat diameter and the upstream pipe **12** diameter. The reduction in turbulence comes about because, while the nozzle **24** increases the average fluid velocity, it does not significantly alter the tangential velocities of the turbulent eddies. Thus the turbulence as a percentage of average fluid velocity is reduced. Tests have demonstrated the ability of nozzles **24** having a beta ratio of 0.67 to reduce the standard deviation of individual flow measurements by about a factor of two, as might be expected since $(1/0.67)^2\approx 1/2$. The use of a nozzle **24** downstream of the turbulence conditioner **16** but upstream of the flowmeter **14** would reduce the standard deviations of the flow of FIG. **6** from 0.5% to 0.25%. The arrangement would halve the $(2\sigma_{mean})$ data of FIGS. **7** and **8**, leading to 100% success even with the 10 barrel proving volume.

It should be noted that the pitch does not have to be fixed. FIG. **9** shows larger holes in some part of the cross section of the conditioner **16**. FIGS. **10** and **11** show the openings **22** are not of equal dimensions, but vary.

Although the invention has been described in detail in the foregoing embodiments for the purpose of illustration, it is to be understood that such detail is solely for that purpose and that variations can be made therein by those skilled in the art without departing from the spirit and scope of the invention except as it may be described by the following claims.

What is claimed is:

1. A method for producing a turbulence conditioner for use with an ultrasonic flow meter in a pipe comprising the steps of:

identifying an effective diameter of an aperture of the flow meter to be disposed in an opening in the pipe through which the flow meter communicates pulses of ultrasonic energy with the interior of the pipe; and

building a conditioner with a pitch between openings in the conditioner which is less than the effective diameter.

2. A method as described in claim **1** wherein the building step includes the step of building walls having a thickness between the openings of the conditioner that are a function of the pitch.

3. A method as described in claim **2** wherein the building step includes the step of building the conditioner with a length that is a function of the pitch.

4. A method as described in claim **2** wherein the building step includes the step of building the conditioner wherein the walls have a thickness between 1/4 to 1/10 of the pitch.

5. A method as described in claim **4** wherein the building step includes the step of building the conditioner wherein the length is 5 to 20 times the pitch.

6. A method as described in claim **5** wherein the building step includes the step of building the conditioner wherein the holes have a cross-section that is two or more sided.

7. A method as described in claim **5** wherein the building step includes the step of building the conditioner wherein the holes have a circular cross-section.

8. A method as described in claim **7** wherein the building step includes the step of building the conditioner wherein the pitch is a function of the meter's maximum velocity.

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